



13th Global Conference on Sustainable Manufacturing - Decoupling Growth from Resource Use

Keeping a factory in an energy-optimal state

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The energy performance of individual machines and peripheral processes in a production system is, for the main part, not sufficiently known. The ECOMATION project aims at solving this problem by developing methods to measure and illustrate energy consumption and save energy in manufacturing processes. A holistic approach enables operators to continuously monitor a factory's energy consumption, based on two control loops: one at the shop floor level (including main processes and peripheral systems) and the other at the factory level, the two loops being interlinked in an additional step. The approach allows for the bidirectional exchange of data between the resources of both main process and peripheral processes and the higher management level. Classical approaches usually consider only the main process at machine level, even though a significant percentage of energy is required by the peripheral systems. The aim of the approach is to keep the manufacturing system in an energy-optimal state.

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Peer-review under responsibility of the International Scientific Committee of the 13th Global Conference on Sustainable Manufacturing

Keywords: energy efficiency; energy monitoring; energy optimization; energy control loop**1. Introduction**

Rising energy prices and an increasing awareness of limited resources and their sustainable use prompts ever more manufacturing companies to strive for an energy-efficient production that, leads to lower costs [1]. An important issue in production organization is the energy-efficient planning and control of production, with a particular focus on machine scheduling [2]. Machine scheduling allocates production orders to available machines, considering quantitative and time restrictions. About 17% of the life cycle costs of a machine tool account for energy costs [3]. The annual energy consumption of cutting machine tools amounts to 150,000 kWh [4]. This shows that the energy-efficient control of machines should not be disregarded.

ECOMATION creates new opportunities for planning production, taking into account energy efficiency, and for intervening during production through control measures.

For a sustainable and energy-efficient production, a holistic approach across different layers and levels of the control hierarchy is compulsory. ECOMATION addresses the issue

of planning and control on the following levels: factory control level (capturing the whole factory), machine level (capturing machines as a resource), electric component level (capturing single components in a machine) and process level (capturing single process steps, such as cutting). Only such a multilevel approach allows for identifying energy losses and addressing them by appropriate measures. As the goal is to control energy consumption in the manufacturing process and the process peripherals and to increase energy efficiency through automation, the project is called ECOMATION. The syllable "ECO" refers to economically and ecologically motivated efficiency, while "MATION" refers to enabling resource efficiency through automation

Control loops have been developed for the factory control level which enable, for example, an energy-efficient scheduling of machinery. For the lower levels (machine level, electric component level, and process level), specific control loops were developed which support an energy-efficient operation of machines. Taking into account the actual situation, such a control loop selects the ideal machine parameters and the operational state.

The approach is designed to enable energy-efficient control across all indicated levels and within the hierarchy. By using consumption models at all levels, predictions can be made for an optimum control. The following article presents a holistic approach for different areas of production planning and control as well as for the machine level, which demonstrated by an operating state optimizer.

2. Initial situation and State of the Art

Current projects want to increase the efficiency of a single machine or process and provide an optimal design of process chains. They develop and implement concepts to support the manufacturing industry in the reduction of energy consumption. These approaches often inform only about consumption sources, including the temporal consumption structure. Factories, however, are complex systems. The "energy" factor takes various forms and energy is used in different areas of a factory. Energy can be produced (energy generation), has to be distributed, will be 'consumed', can be recovered, and is lost (energy losses). The focus here is on energy conversion and distribution in a factory. A major part of energy will be used by peripheral applications and processes in non-value added sectors [5]. Engelmann shows, in an example of car body manufacturing, that peripheral applications such as exhaust ventilation systems, lighting equipment, and air supply account for 50 percent of total energy consumption in the building. For this reason, it is imperative to take peripheral systems into account [5]. According to Schenk and Wirth [6], three levels of peripheral systems can be distinguished. This approach has been adopted by ECOMATION.

Müller also deals with the energy-efficient planning and operation of factories. He developed methods and checklists in the field of energy efficiency of factories, as well as management and target systems related to energy efficiency [7]. These universal methods can be partially applied to the specific problem. Müller focuses on energy-efficient factory planning and includes planning activities such as system analysis and system design. Another difference is that ECOMATION accomplishes the control of energy consumption through operations planning measures, an aspect not considered by Müller.

Production planning and control includes measures required for the production of an order, for instance by job planning [8]. Reinhart et al. selected different fields of action for production planning and control which result in a reduction of energy consumption. These fields are: energy-optimized sequence of production orders, selection of an energy-optimal resource (machine with minimal energy consumption), harmonization of energy consumption, accumulation of buffer and idle times, and definition of an energy-optimal batch size [9]. Production planning and control influences the energy performance of a factory (energy consumption) particularly by the selected resource and the determination of target time.

Also the use of software system for material flow simulation is a possible approach to verify energy-oriented

goals in manufacturing systems [10]. One approach provides Putz et al. [11]. He developed a framework for energy-sensitive production control (manufacturing execution system) to support an energy-sensitive material flow simulation. This framework includes the enterprise control level, the manufacturing control level and the manufacturing level. The software solutions implemented in the aforementioned levels can contribute to a decreased energy utilisation.

As ECOMATION is complemented by a comprehensive methodology for energy-efficient operation, an actual operating optimum can be achieved. The approach allows the identification of efficient resources based on an optimal control of consumers. Subgoals are:

- detecting the energy consumption of processes, equipment and components,
- predicting energy consumption for various types and use cases,
- automated, situation- and requirement-oriented optimal control parameters and processes that have an impact on energy consumption based on energy control loops at machine level, as well as
- ensuring a company's energy efficiency by remote power control loops in planning and control.

3. Basic Methodology

3.1. General approach

To continuously control a factory and keep it in an energy-optimal state, the first thing to do was to create models of the main processes and the peripheral systems. Then, the modeled resources were linked to specific status-based energy profiles. For example the following machine conditions are possible: off, warm up, wait, work, error, save. Interfaces served to connect the models to the shop floor to allow their parameterization by the recorded field data. The model is connected 'bottom-up' to the management level. The superior management level records, for example, data on machine status, loading times and consumption. The basics and the implementation of the modeling approach are illustrated in [12]. Figure 1 shows the general approach, particular the planning and optimization logic.

First of all, the status available for each resource was used for modeling the resources and the energy demand was calculated for each status. An interface between shop floor and model allows for the integration of field data (energy consumption values). In addition, the times are defined, i.e. how long the status lasts and when it occurs. This information can be derived from the standard times set out by operations planning.

With a view to the shop floor, i.e. the manufacturing resources, several optimizers for the manufacturing processes and the machine components were developed to control the machines and the machine components in an energy-optimal manner. These optimizers are united in the so-called machine-level control-loop.

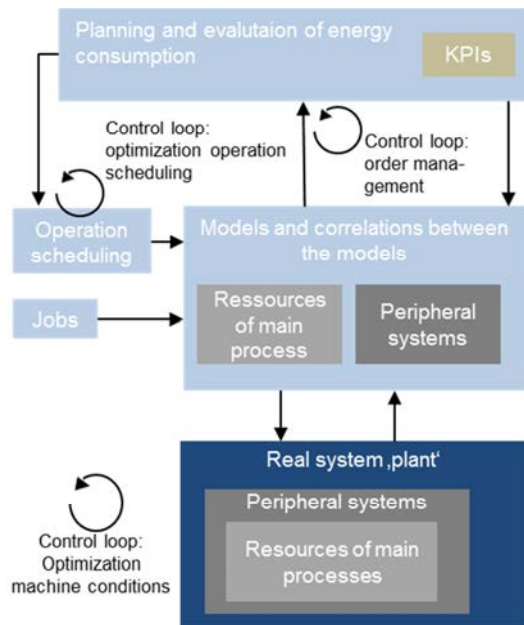


Fig. 1. general approach

There are also control loops at the interface between model and higher-level management system, the so-called factory-level control loops. They can perform operations planning activities, make improvements in the order management, pass on information and data to the shop floor, and optimize the control of the machine status.

3.2. Interaction between control loops

As shown above, the methods and shop floor systems for modeling energy consumption are integrated with a simulation environment where the complete system including peripherals and production and process control are mapped. A discrete event simulation tool is used as a simulation environment. A key performance indicator (KPI) system provides the basis for planning the expected energy demand on the shop floor. This KPI system basically contains the indicators of time (lead time), costs, quality and energy. The indicators can be weighted individually, depending on the manufacturing strategy [13]. The KPI system directly interacts with the simulation model to form the model. The model, in turn, is connected to existing systems, such as the order management system, to integrate real orders into the simulator. Then, an optimization run is performed in the simulation model to feed the results back to the KPI system, so that an evaluation of the energy demand on the shop floor can take place. The different control loops, consisting of shop-

floor system and planning and control system, are complemented by the simulation model and report the results to the higher-level management system. This enables constant control, keeping the factory in an energy-optimal state.

3.3. Machine condition optimization tools

The first control loop performs the task of optimizing the so-called 'machine-related' peripheral components. A well-known case is that of lubricant and coolant pumps, which account for an important part of energy consumption in machining processes. For example, the amount of energy consumed by the Gildemeister CTX 420 linear lathe (very commonly used in the machining industry) for pumping and cooling operations is much higher than that for performing the process itself and for activating the components of the machine.

A good example of optimization would be to avoid unnecessary pumping during periods in which the machine is not working on a piece. To be able to 'fine-tune' the peripherals involved in the process, a special component was developed by ECOMATION. This component is able to control at what moment the peripheral elements should best come into action, based on the future states of the machines.

The prediction of states refers to two levels. The first one is machine-level control-loop, which is based on known parameters of the production program and on characteristics of the peripheral components (i.e. coolant pump). The second one is based on the planned workload of the machines. This basically refers to when a machine stops the current production process before the fabrication of a new piece is started. This enables machines to enter into an energy-saving standby mode (or even be shut down) whenever possible. It also takes account of additional parameters linked to the new piece to be processed, such as material and tools. Within ECOMATION, the second control loop, also called factory level control loop, is responsible for performing job scheduling in an energy-efficient manner (as explained in the section below).

3.4. Energy-efficient job scheduling

The aim at the production control level, i.e. the factory-level control loop, is to identify potential losses in plants and process peripherals, for example unnecessary standby times, to initiate improvement measures. This is accomplished by energy planning, which results from detailed planning and energy monitoring as well as from a comparison between actual energy consumption and forecasted consumption. Detailed production planning and control activities are carried out by the ECOMATION planning tool in seven steps, as shown in figure 2.

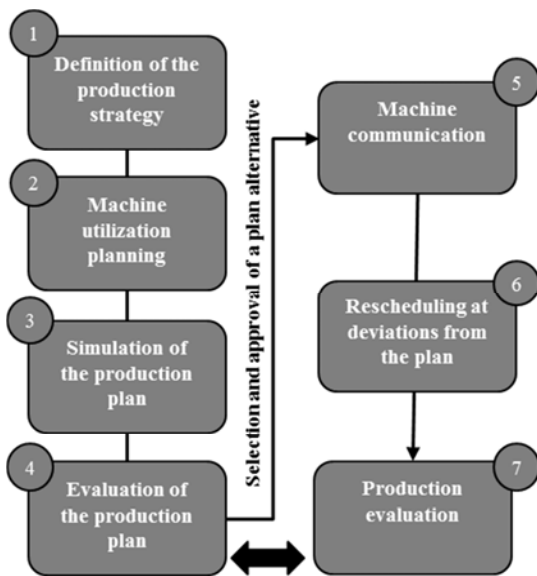


Fig. 2. overview planning tool.

In the first planning step, the production orders to be processed are read from the superior ERP system into a job scheduling tool. The latter considers all orders needed in the selected period (e.g. for a production shift). In addition, the production strategy is selected. The production strategy reflects the target variables to be optimized, such as short lead time, high machine utilization, low intermediate stocks, or high energy efficiency. In the second step, based on the chosen production strategy, the planning tool creates a machine schedule considering all target priorities. The jobs are distributed to the available production resources using a scheduling algorithm. In the third step, the ECOMATION planning tool resorts to an information technology for simulating production systems to allow for further detailing. Prior to production release, the production structure depicted in the simulation is used to validate what material flows are necessary for the generated production planning proposal. The simulation provides forecast data on the expected production lead times, the intermediate stocks (work in progress), as well as the expected energy consumption. In the end, the indicators representing time, quality, cost and energy are displayed in a so-called KPI cockpit in the planning tool, providing the basis for the evaluation. The evaluation aims at optimizing production, based on the factors of time, cost, quality and energy. The cost factor, for example, is reflected in the equipment costs. The energy costs that are part of the machine-hour rate can thus be flexible. On the one hand, they depend on the reference time and, on the other hand, on a consumption-based demand charge. In addition, power consumption is shown both over time and allocated to the respective production resources and manufactured products.

The planning proposal can be cached and a new planning run be created, reflecting the altered optimization criteria. A supplementary monetary evaluation of planning proposals allows the selection of the most economical alternative by the production planner. Thus, ECOMATION provides a methodology for model-based planning and evaluation of

energy efficiency for machining processes [14]. The planning proposal is passed on to manufacturing by releasing the selected planning alternative. How communication between planning and production facilities works via OPC-UA standard is described in the next chapter.

While production is going on, the current machine states and operational data on finished production quantities are reported back to the control component of the ECOMATION tool. It records the progress in time and quantity and compares it to the plan and then allows for interventions in case of deviations from plan. As such deviations from plan are not unusual in real-world manufacturing, controlling interventions into the ongoing planning process are often necessary. Here, two types of incidents affecting the production process are distinguished. A minor incident, such as the deviation of real from predefined processing time, only leads to a postponement in the production order sequence, provided the planning reserve allows for it. If the planned orders cannot be postponed, or if a major disruption occurs on the shop floor, such as a machine breakdown, a new planning run can be initiated in the order planning tool that is based on the current state of completion.

In the final process step, energy profiles (fingerprints) are calculated for all production resources employed, based on the manufacturing data that were reported back. Fingerprints are a profile of the energy usage of every machine, further differentiated by state, material, product, tool, production program, and other. The fingerprints therefore accommodated to the actual energy consumption in the plant, according to the respective operating conditions. For this purpose, the recorded energy consumption values are assigned to the machine states to determine an average value for future planning runs. The regular feedback of actual manufacturing data and their comparison with original planning data creates a control loop which continuously improves the data used for planning.

3.5. communication among resources and management system

In order to depict the energy flows in the production system, a model-based approach is necessary. Other requirements encompass the functionalities of a monitoring system, the continuous capturing of field data, and a machine control system.

The results showed that an adequate methodology for a bidirectional communication between the resources and the planning level had to be developed. A messaging system was created to provide the key functionality. It is capable of sending top-down and bottom-up message within the communication architecture [15].

To connect power consumption control at production control level to energy consumption control at control level, OS-independent protocols such as OPC UA or the Simple Object Access Protocol (SOAP) are used for network support. The VDI standard for MES Communication was chosen for communication between planning level and machine control unit [16]. The use of VDI standards allows for a faster transfer of the developed project solutions to market.

Another reason for applying standards in accordance with VDI directive is to remain vendor-neutral. As this must also apply to communications, OPC UA was selected. The format of the OPC Foundation enjoys a high level of acceptance and is widely available in the industry, due to the openness, independence and integrity of the standards [17]. In addition, the server-client architecture enables a fast and stable implementation of the project requirements. Figure 4 outlines the planned communication between planning and control levels within ECOMATION.

The structure allows the planning tool to control machines in real time, regardless of their type and number. The special features of the machine tools can therefore easily be visualized in the tool. Compliance with VDI standards also allows the transfer to other applications without greater need for adjustment.

3.6. Energy efficient planning and control tool

Based on methodology, communication architecture (OPC UA) and data exchange standard (VDI 3600), ECOMATION was able to create a planning and control tool, fulfilling the five following functions:

- Application of a planning algorithm to enable the energy-efficient scheduling and assignment of production orders to machines. Other optimization factors in planning and scheduling, the so-called logistical target values, are also considered: delivery reliability, order backlog, machine workload, and throughput time [18].
- Control of the respective machines, disregarding particularities and special parameters of each piece of equipment. By using the OPC UA interface and the unified communication standard based on the VDI nodes, the tool is furnished with a uniform communication method, making the particularities of each machine fully visible.
- Integration of feedback data from the shop floor (delays, machine malfunction, etc.) to adapt the production plan accordingly. Minor delays are recalculated with ease, whereas major disturbances call for the re-application of the planning algorithm in order to assure the energy efficiency and harmony of the production system (workload distribution among the machines)
- Permanent re-calculation of energy fingerprints, adapting to changes in the energy efficiency of equipment. The energy consumption of a machine can change due to many factors. One of them is the effect of wear; as improved planning has an overall effect on the energy requirements of equipment, it is necessary to constantly revise the values to obtain a valid model.
- Calculation of KPIs in real time, not only considering technical (energy consumption) but also financial aspects (energy cost with actual production plan)

The tool, programmed under an object oriented language, is easy to handle. Two interfaces must be included:

- Simulation software: the previously mentioned simulation model is used by the planning tool in order to confirm the

calculated energy consumption and plausibility in the production plan. The consideration of stochastic factors is key in order to achieve a reliable plan.

The model runs currently on entity-based simulation software, i.e. Plant Simulation 10.

- OPC UA connection: Each machine can be considered as an OPC server and for this reason the tool must be able to identify and communicate with each of them, simulating an OPC Client application.

Both interfaces were included, making use of the commercially available APIs. Special consideration had to be given to the OPC interface, as time consumed for communication is a critical factor in real-time control of machines to avoid differences between planned and actual time.

4. Scenario and Benefit

This paper has analyzed the advantages of applying the ECOMATION concept and solutions to the metalworking industry. But this idea can also be transferred to a great number of other industries and manufacturing systems. An excellent example is the manufacturing of semiconductors. A typical semiconductor manufacturer uses as much power per year as 50000 homes do. That is an equivalent of 100 megawatt per hour.

Semiconductor producers have a complex production system, consisting of many machines where status optimization would be possible. Particularly interesting are the possible savings offered by the peripheral systems, as described in figure 3.

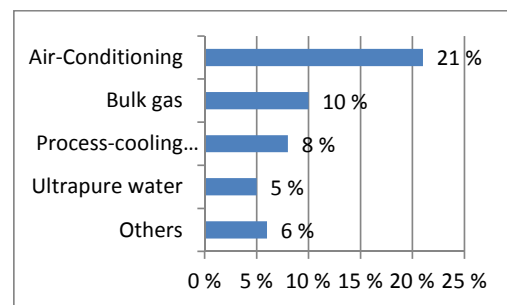


Fig. 3. potential savings in % in a semiconductor factory [19]

Up to 30% of these energy costs can be saved [19]. From these overall savings, air conditioning alone amounts to more than 20%. This means that approximately 6.3% of the energy costs could be saved by just optimizing runs of the air-conditioning on the manufacturing systems.

Furthermore, studies have shown that the exhaust volumes of most of these plants are higher by 20 to 50% than specified and required [19].

It is then clear that there is a huge possibility to save energy and money just by precisely controlling when the peripherals (i.e. air-conditioning) act. Applying the approach of ECOMATION would mean for a manufacturer to be able to activate the peripherals only when needed. The order

scheduling and the requirements of the production are known, simulated and optimized, in order to achieve the coordination of the involved systems that represent the minimal energy consumption.

5. Conclusion

ECOMATION represents a new approach on energy optimization as the main focus resides on making the most of the existing manufacturing infrastructure.

The developed tool and simulation components serve as a demonstrator of the functionality of the concept. Every interested enterprise should be able to take the proposed methodology and adapt it to their current planning and control systems in the short or medium-term. In contrast, most other approaches for the optimization of energy consumption are mostly only possible on a long-term base, as they require big investments and adaptations to be made.

The future phases of the ECOMATION project include the transfer to industry partners in order to further advance the methodology.

Acknowledgements

We express our thanks to the German Research Foundation (DFG) which supported the work presented here as well as our ongoing research through the grant for the Research Unit FOR 1088 'ECOMATION'.

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